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Application of aspen plus for municipal solid waste plasma gasification simulation: case study of Jatibarang Landfill in Semarang Indonesia

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Abstract. The objective of this study is to apply the plasma gasification technology for MSW treatment. The gasification model used Gibbs free energy minimization approach using the Lagrange multiplier method. This model was simulated using the Aspen Plus software. The feedstock of plasma gasification was the MSW in Jatibarang landfill. To verify the model, RDF of Minutillo et al., 2009 was tested. Simulation and modeling of plasma gasification was carried out by air, 60% air mixture and steam 40%, air mixture 40% and steam 60%, as plasma gas, respectively. For 1 kg MSW per second yields hydrogen in mole fraction of 32.64%, 36.74%, 38.51%, while for CO was 31.25%, 26.75%, and 23.35%. The efficiency was 45%, 34% and 38% respectively. Efficiency and the highest of carbon monoxide produced were achieved when only air was used as the plasma gas. The addition of steam as the plasma gas increases hydrogen production but reduces carbon monoxide production. The greater the amount of vapor, the more hydrogen is produced.

1. Introduction

Although the application of plasma gasification to MSW management is a relatively new concept, many studies have revealed that plasma gasification is an attractive MSW treatment option compared to other processes [1]. Plasma gasification is partial thermal oxidation in an oxidant starved medium, which steam, air or oxygen is supplied to the reaction as an oxidizing agent [2]. The high temperatures during the process are generated by the torch plasma where the oxidizing agent is converted to plasma. At this high temperatures, the MSW will break down to their elemental form [3]. The organic fraction of the MSW converted into syngas (H₂ and CO) and the inorganic fraction converted into vitrified slag [4].

The objective of this study is to apply the plasma gasification technology for MSW treatment in Jatibarang region in Semarang province, Indonesia. The landfill has been in operation since May 1992 and was due to be decommissioned in 2008 [5]. Because of difficulties in finding a new location, its



serving period is renewed with some modifications such as the use of green belts and covering lands. Those are some of the reasons as to why processing waste to energy (WTE) is deemed a preferable method in order to reduce the amount of waste dumped into landfill [6]. WTE is a promising technology and has gained more attention over the last two decades due to higher demands for cleaner fuels and chemical fuels, and also to reduce greenhouse gas emission [7].

2. Material and Method

2.1. Characteristics of feedstock

The characteristics of msw includes heating value, proximate and ultimate analysis of MSW (table 1). The analysing of MSW was performed at tekMIRA (Center for Study and Technological Development of Mineral and Coal of the Ministry of Energy and Mineral Resources, Bandung, Indonesia).. The ultimate analysis was performed to figure out the percentage weight of C, H, N, O, and Sin MSW samples [8], while proximate analysis involves the determination, again in weightpercentage, of water content, volatile material (VM), fixed carbon (FC) and ash. The heating value of MSW was measured using a bomb calorimeter based on ASTM D.5865. Table 1 shows ultimate and proximate analyses, heating value of MSW. Metal and glass were excluded because its were taken by scavenger.

The Testing Standards at TekMIRA to determine the contents of C and H in the MSW is accomplished using the methods outlined in standard ISO 625 ASTM D.3178[9][10], while the O content is 100%-(C+H+N+S+Ash). The N and S content are determined following standard ISO 332 ASTM D.3179 and ASTM D.4239, respectively. The methods to determine moisture and ash are ISO 11722ASTMD.3173andISO 1171ASTM D.3174,respectively.

Table 1.Charasteristics of Feedstock

Charasteristics of Feedstock		Parameters Performance of Plasma Gasifier
Ultimate Analysis (wt. % db)		
C	43.71	H2, CO, CO2, N2, CH4, H2O, H2S.
H	7.73	
N	1.95	
S	0.40	
O	37.66	
Proximate Analysis (wt. %)		
Fixed Carbon	12.82	HHV LHV
Volatile matter	77.66	
Ash	9.51	
Water content	20	
HHV (kJ/kg)	18530.4	
LHV (kJ/kg)	16013.6	

2.2. Energy Balance

P_{pl} is the power input to the reactor. A part of the energy supplied will be lost in the torch ($P_{lost,torch}$) and some will be lost in the reactor ($P_{lost,react}$). Meanwhile, the remaining energy will be

used to volatilize the MSW ($P_{msw,gas}$) and heat up the syngas up to reactor temperature (T_r) $P_{heat,syn}$. Hence, the energy balance (fig.1) is:

$$P_{pl} - P_{lost,rad} - P_{lost,react}(T_r) - P_{msw,gas}(T_r) - P_{heat,syn}(T_r) = 0 \quad (1)$$

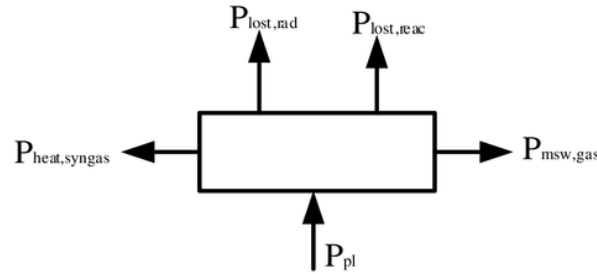


Figure 1. Energy equilibrium balance

$P_{lost,rad}$ can be calculated by measuring the reactor surface temperature and the surrounding temperature. This power is a loss depending on the temperature at the T_r reactor and the temperature of the leaving plasma gas reactor T_{pl} . T_{pl} temperature equal to T_r if mixing and heat transfer is complete plasma for the material treated during the residence time in the reactor is ensured.

The process output from the gasification reactor include Syngas heat value (LHV_{syngas}), synthetic gas composition, and efficiency and mass flow rate of syngas. Gasification efficiency is calculated using:

$$\eta = \frac{\dot{m}_{syn} LHV_{syn}}{\dot{m}_{msw} LHV_{msw} + P_{pl} / \eta_{pl}} \quad (2)$$

where \dot{m}_{syn} and \dot{m}_{msw} are mass flow rate of syngas mass and feedstock, respectively, LHV_{syn} and LHV_{msw} are heating values of syngas and feedstock, respectively, and P_{pl} is the plasma power.

2.3. Modelling Simulation of Plasma Gasification for Municipal Solid Waste

Aspen Plus comes with a unit operation model known as RGIBBS that counts both chemical and thermodynamics equilibriums based on minimized Gibbs free energy of the system. This model allows users to specify pressure, temperature, and heat that adiabatic, constant pressure, or constant temperature can be set. This gasification equilibrium model is taken as of zero dimension as mixtures in the reactor are assumed to be evenly mixed, without taking spatial and time parameters into account. In reality, different types of gasifiers have complex hydrodynamics that causes gas composition to stray from its equilibrium composition.

Moreover, this model assumes that reaction speed is fast enough and enough residence time is met that facilitate a condition of equilibrium. Chemical gasification kinetics involves many complicated chemical reactions, that it is hard to accurately represent gasification using a kinetic model. Other than that, a kinetic mechanism to convert solid fuel, especially waste, for primary products is not yet known [11]. Therefore, an equilibrium model allows the prediction of combustion and gasification product from complicated technical fuels.

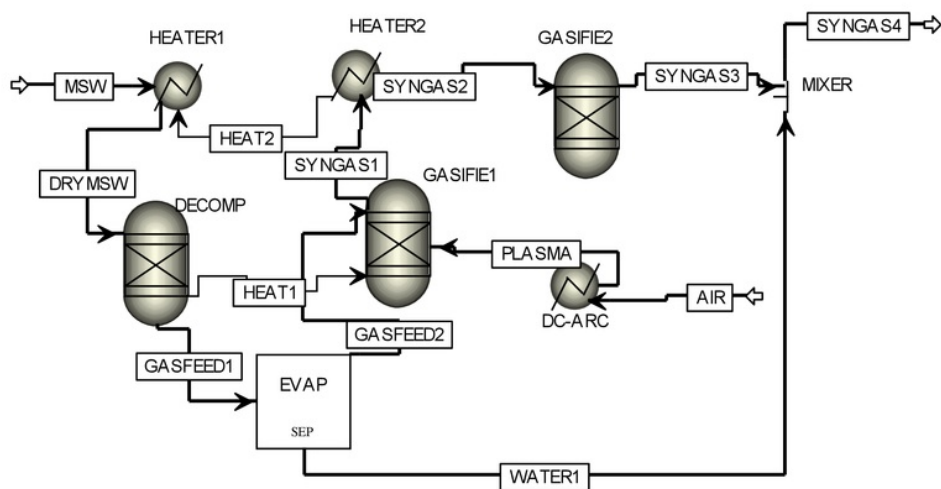
The components in Aspen Plus © are classified as conventional or non-conventional. Conventional components are properties inherent in the database of Aspen ©. Non-conventional components are non-homogeneous basic data components that do not have consistent components and are not available in Aspen. These components include coal and biomass that must be given physical attributes, as defined by proximate, ultimate, and sulfur analyses. A property method must also be chosen to calculate the enthalpy and density of substances. To do this, a method such as HCOALGEN

and DCOALIGT are chosen to respectively calculate enthalpy and biomass for materials that do not have consistent compositions and are not available in Aspen. These property methods employ correlation statistics to calculate specific heat, enthalpy, and density of coal and coal substances derived from ultimate, proximate, and sulfur analyses. As waste is technically representable as fuel, these property methods are also used to calculate thermodynamics properties of waste. The HCOALGEN property method offers different options on how component forming enthalpy is calculated. To do this, forming enthalpy is calculated based on the HHV value of each substance, as required by the user.

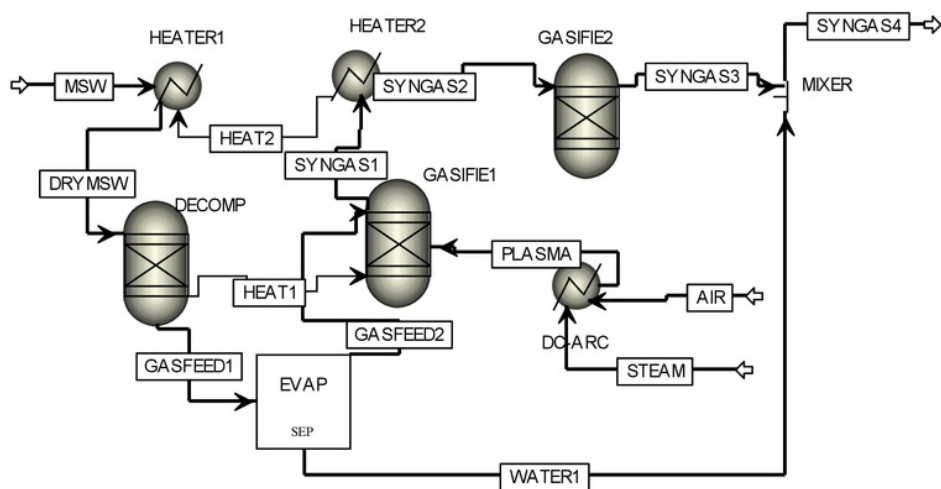
The block of operation description for simulation is shown in table 2. Wet waste is dried in the heat exchanger HEATER1 up to 120°C and is heated by the heat of syngas and turns into dry waste DRYMSW. The RGIBBS equilibrium reactor does not take non-conventional components as reactants. Hence, dry waste must be degraded into conventional components to be used by the RGIBBS block. This conversion is carried out with an RYIELD block, which is a reactor model that produces known products. The flow of feedback fuel enters DECOMP, where it is decomposed into its forming constituents of H₂, O₂, N₂, H₂O, S, C, and ASH. A Fortran calculator script then interacts with the DECOMP to allow fuel decomposition to be calculated based on proximate and ultimate analyses of non-conventional components. Carbon content of feedstock is converted into solid carbon graphite. This species is now included in the flow known as GASFEED1, continues as a flow to the separating block SEPAR, where water is separated from the fuel into GASFEED2. GASFEED2 is then turned into reactants for the HT block. An oxygen flow that represents gasification oxidants also enters the HT reactor, and the product outflow. Heat flow HEAT1 connects DECOMP and GASIFIE1 and represents the energy required disintegrating solid fuel. Even though HEAT1 reacts with GASIFIE1, this reactor is still considered adiabatic as DECOMP calculates the amount of heat required to decompose and retract fuel from GASIFIE1. GASIFIE1 is determined by the zero heat duty and any given pressure. As this is adiabatic, energy force conversion GASIFIE1 calculates the temperature of adiabatic reactor the product. Figure 2(a) –(b) depicts the flow sheet process for an adiabatic gasification reactor where the mixture mixes with plasma gas and creates plasma torch. Plasma gas, in the form of either air or a mixture of steam and air enters the GASIFIE1 reactor after being heated for up to 4000°C in the DC-ARC heat exchanger that models plasma torch. Plasma torch efficiency is assumed to be 90% [12]. In the high temperature plasma block, GASIFIE1, the method of minimizing Gibbs' free energy is applied to break syngas composition in the output reactor in a condition of chemical equilibrium. In order to ensure that the decomposed fuel is intact, the output temperature of GASIFIE1 block is set at 2000°C by doing iteration on the amount of plasma gas flow into the reactor. Output SYNGAS1 from GASIFIE1 reactor enters HEATER2 to be cooled down into SYNGAS2 and in turn enters the GASIFIE2 block. This block is a model of gasification reaction for low temperature zone into the plasma reactor (1450°C). The output of block GASIFIE2 is named SYNGAS3 and mixes with WATER1 from SEPAR, then turns into SYNGAS4.

Table 2. Block of operation description

Block Name	Block Type	Description
HEATER1	HEATER	Non-stoichiometry reactor model in which yield distribution is known.
HEATER2	HEATER	Functions to cool down syngas that in turn represents the low temperature zone in the reactor.
DC-ARC	HEATER	Models plasma torch
DECOMP	RYIELD	Decomposes waste into its element constituents.
SEPAR	SEP	Separates water from the other gases.
GASIFIE1	RGIBBS	Reactor model that solves the multiphase equilibrium using
GASIFIE2	RGIBBS	minimized Gibbs' free energy
MIXER	MIXER	Mixes syngas products and water vapor.



(a)



(b)

Figure 2. Model flowsheet (a) air as plasma gas (b) air+steam as plasma

2.4. Model Validation

In order to validate the model, the fuel used by Minutillo et al., 2009 [12] was tested, and for the plasma gas, an air composition of 40% O₂ and 60% N₂ was used and operated in atmospheric pressure. Results of syngas from RDF was used Minutillo are given in Table 3

Table 3. The Model Validation

Mole fraction of components	Minuttilo et al., 2009 (%)	The model (%)
H ₂	31.48	31.50
CO	38.73	38.75
CO ₂	0	0
N ₂	16.32	16.42
CH ₄	0	0.00
H ₂ O	12.5	12.66
HCl	0.31	0.31
H ₂ S	0.22	0.22
COS	0.01	0.01

2.5. Performance of Plasma Waste Gasifier

Simulation results of gas composition, syngas heating value, plasma torch energy consumption, gasifier output temperature, and plasma gasification efficiency with air and a mixture of air and steam are given in Table 4. Plasma can directly serve as gas without the need of an oxidation media as it has high energy content, but this scenario usually results in carbon production that sacrifices syngas production. Therefore, an amount of stoichiometry of the air, or a H₂O mixture is added [13]. In their laboratory experiment, Nishikawa et al. (2004) [14] reported that water vapor allows the reduction of charcoal weight and increases hydrogen production. Zhang et al., (2012) [15] also studied the effects of steam injection on a pilot scale thermal plasma gasification plant for waste, and found that cool gas efficiency and syngas product can be enhanced by increasing the amount of injected steam. All fuels result in CO₂ on a low scale. This is due to the fact that the energy required for gasification comes from the plasma torch.

Table 4. Results of the plasma gasifier

Mole fraction of syngas (%)	Plasma		
	Air	60%Air + 40%steam	40%Air + 60%steam
CO	31.25	26.15	23.85
CO ₂	0.13	2.62	3.54
H ₂ S	0.11	0.1	0.09
NH ₃	0	0	0
CH ₄	0	0	0
C	0	0	0
H ₂ O	12.28	20.85	25.8
H ₂	32.64	36.74	38.51
O ₂	0	0	0
N ₂	23.59	13.54	8.22
S	0	0	0
HHV syngas (MJ/kg)	5.399	5.139	5.057
LHV syngas (MJ/kg)	5.321	5.045	4.954
Temperature °C	1233	1250	1142
Waste flow (kg/sec.)	1	1	1
Syngas flow (kg/sec.)	1.7	1.7	1.7
Air flow (kg/sec.)	0.782	0.482	0.3
Steam flow (kg/sec.)	-	0.3	0.482

Power of plasma discharge (MW)	3.8	8.25	5.8
Efficiency η	45%	34%	38%

Results of simulation and modelling of plasma gasification for 1 kg of MSW per second show that the generated mole fractions of hydrogen is 28.06%, 32.53%, and, 34.46%, while the mole fractions of CO is 27.53%, 22.73%, and 20.63%, each for air, a mixture of air and steam, and steam as plasma. Meanwhile, the efficiency is 45%, 34%, and 38%, respectively.

3. Conclusion

The efficiency and the amount of carbon monoxide resulting from the plasma gasification are highest when only air is used as plasma. The addition of steam as plasma gas increases hydrogen production but decreases the production of carbon monoxide..

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